

THE EXTREMELY HIGH PEAK ENERGY OF GRB 110721A IN THE CONTEXT OF A DISSIPATIVE PHOTOSPHERE SYNCHROTRON EMISSION MODEL

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ABSTRACT

The Fermi observations of GRB 110721A (Axelsson et al. 2012) have revealed an unusually high peak energy ~ 15 MeV in the first time bin of the prompt emission. We find that an interpretation is unlikely in terms of internal shock models, and confirm that a standard black-body photospheric model also falls short. We show that dissipative photospheric synchrotron models ranging from extreme magnetically dominated to baryon dominated dynamics, on the other hand, are able to accommodate such high peak values.

1. INTRODUCTION

High energy (> 100 MeV) observations of gamma-ray bursts (GRBs) have gained renewed interest since the launch of Fermi LAT (Atwood et al. 2009). This instrument has revealed a curious diversity in the high-energy behavior of GRBs and consequently represents a new challenge for models (see Mészáros 2012, for a recent review). For GRB 110726A (Axelsson et al. 2012), the extremely high $\varepsilon_{\text{peak}} \approx 15$ MeV peak energy (peak of the $\varepsilon F_\varepsilon$ spectrum), which was observed right after the onset of the burst, makes its interpretation in the framework of a simple internal shock synchrotron model challenging. Interpreting the peak as a modified black-body from a simple photosphere is also difficult, as it can only account for energies up to few MeVs, and even the subsequent time-bins show peak fluxes which, even though lower, are still unusually high. Such black-body photosphere models have been considered by Fan et al. (2012) to explain a $L \propto \varepsilon_{\text{peak}}^{0.4}$ correlation found by Ghirlanda et al. (2012), but as shown by Zhang et al. (2012), they must lie below a line in the $\varepsilon_{\text{peak}} - L$ plane which excludes the observed values for GRB 110721A.

Here we show that the high peak energy and luminosity of GRB 110721A can be interpreted in the framework of a different class of photospheres, where dissipation occurs near the photospheric radius, and the spectrum is characterized by a synchrotron peak. Dissipative synchrotron photospheres have been considered for baryonic dominated regimes by, e.g. Rees & Mészáros (2005); Pe’er et al. (2006); Beloborodov (2010) and for magnetically dominated regimes by Giannios (2006); Tchekhovskoy et al. (2012); Giannios (2012). Here we consider such photospheres for an arbitrary acceleration law, characteristic of either a baryonic or a magnetic dominated regime. Also the observed thermal bump close to 100 keV is naturally incorporated in this model.

2. DYNAMICS, NON-DISSIPATIVE PHOTOSPHERES AND INTERNAL SHOCKS

The initial acceleration behavior of the jet material is taken to be given by

$$\Gamma(r) \propto \begin{cases} r^\mu & \text{if } r < r_{\text{sat}} \\ \text{const.} & \text{if } r_{\text{sat}} < r, \end{cases} \quad (1)$$

where r_{sat} is the saturation radius beyond which the flow reaches its asymptotic coasting value $\eta = \langle L \rangle / \langle \dot{M} c^2 \rangle = \Gamma_{\text{final}}$. Based on the analysis of (e.g. Drenkhahn 2002; Mészáros & Rees 2011), for simple conical magnetically dominated models $\mu = 1/3$, while in the simple baryonically dominated case $\mu = 1$. More general cases involving different magnetic geometries or flows where the opening angle varies with radius will generally lie between $1/3$ and 1 . The case of $\mu = 1/3$ has been further developed by Veres & Mészáros (2012), including the effects of the shocked electrons at the external deceleration radius; the generalized magnetic model including an arbitrary acceleration law $1/3 \lesssim \mu \lesssim 1$ is considered in more detail in Veres et al. 2012 (in preparation). Here we calculate the relation between the luminosity and the peak energy based on the dissipative synchrotron photospheric model for values of μ between the two extremes, in the context of GRB 110721A. We denote physical quantities through the usual $Q_x = Q/10^x$ notation.

As discussed by Zhang et al. (2012) in the usual $\mu = 1$ baryonic dynamics the photospheres usually arise in the $r > r_{\text{sat}}$ region, and in the absence of dissipation the black-body peak energy and flux representing a putative Band spectrum peak would fall below a line which excludes the observations of GRB 110721A.

Internal shocks may also be considered as a possible explanation, since this model is usually used for interpreting the prompt gamma-ray emission (Rees & Meszaros 1994). For variability timescales t_v seconds and an average Lorentz factor η the internal shock occurs at a radius $r_{\text{IS}} = 2 \eta^2 c t_v \approx 5 \times 10^{14} t_{v,-1} \eta_{2.5}^2$ cm and for the usual magnetic field prescription one expects an observer frame peak energy of $\varepsilon_{\text{peak}}^{\text{IS}} \approx 1 L_{52}^{1/2} \eta_{2.5}^{-1} t_{v,-1}^{-1} \epsilon_{B,0.3}^{1/2} \epsilon_{e,0.5}^2 \frac{2}{1+z}$ MeV, an upper limit based on a variability $t_v = 10^{-1}$ s (the light curve of GRB 110721A is rather smooth, FRED-like, suggesting a longer variability time). A some-

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what different calculation including pair formation (Guetta et al. 2001) indicates an upper limit $\varepsilon_{\text{peak}} \lesssim 1 L_{52}^{-1/5} \epsilon_B^{1/2} \epsilon_e^{4/3} \eta_3^{4/3} t_{v,-3}^{1/6} \frac{2}{1+z}$ MeV which is more stringent. Thus, standard internal shocks cannot explain this burst.

3. A DISSIPATIVE PHOTOSPHERE MODEL

Photospheric radius We consider a dissipative photosphere, where a substantial fraction ~ 0.5 of the bulk kinetic energy is converted into random particle energy. An extra spectral component coming from the interaction of the photospheric photons with shock-accelerated electrons at the external deceleration radius is neglected here, as this produces a GeV range contribution, whereas 110721A has only a tentative GeV component. The photosphere arises at optical depth $\tau = 1$, in a jet which initially accelerates as: $\Gamma = (r/r_0)^\mu$. Here r_0 is launching radius at the base of the jet. The value of the photospheric radius can be expressed in terms of a critical Lorentz factor (Mészáros & Rees 2000) which, generalized to an arbitrary μ , is given by

$$\eta_T = (L\sigma_T/8\pi m_p c^3 r_0)^\mu / (1+3\mu). \quad (2)$$

For $\eta > \eta_T$, the photosphere occurs in the accelerating phase, $r_{\text{ph}} = \eta_T^{1/\mu} (\eta_T/\eta)^{1/(1+2\mu)}$, while for $\eta < \eta_T$, it is $r_{\text{ph}} = \eta_T^{1/\mu} (\eta_T/\eta)^3$. The saturation radius is $r_{\text{sat}} = r_0 \eta^{1/\mu}$.

The photosphere occurs in the acceleration phase if $\eta > \eta_T$, which is typical for a magnetically dominated ($\mu = 1/3$) case, where $\eta_T \simeq 120 L_{53}^{1/6} r_{0,7}^{-1/6}$. On the other hand, the photosphere is in the coasting phase for $\eta < \eta_T$, which is typical for baryonic cases ($\mu = 1$), where $\eta_T \simeq 1300 L_{53}^{1/4} r_{0,7}^{-1/4}$. The photospheric radius can be increased by a factor of \sim few by the presence of pairs (Bošnjak & Kumar 2012; Veres & Mészáros 2012).

Synchrotron peak We expect that about half of the total luminosity will be converted to radiation close to the photosphere (Giannios 2012). The peak energy will form at moderate optical depths $\tau \geq 1$. The dissipation is expected to occur in mildly relativistic shocks with relative Lorentz factors of $\Gamma_r \gtrsim 1$, the random Lorentz factor of the shock-accelerated electrons is $\gamma_{e,\text{ph}} \approx \epsilon_e (m_p/m_e) \Gamma_r \approx 600 \epsilon_{e,0.5} \Gamma_{r,0}$, where ϵ_e is the fraction of the energy in electrons. The peak synchrotron energy can be expressed as $\varepsilon_{\text{peak}} = \frac{3q_e B'_{\text{ph}}}{4\pi m_e c} \gamma_{e,\text{ph}}^2 \frac{\Gamma_{\text{ph}}}{1+z}$, where $B'_{\text{ph}} = (32\pi \epsilon_B m_p c^2 n'_b)^{1/2} \Gamma_r$. The physical constants have the usual meaning. $\epsilon_B \lesssim 1$ is the fraction of the energy in magnetic form, $n'_b = \dot{L}/4\pi r_{\text{ph}}^2 m_p c^3 \Gamma_{\text{ph}} \eta$ is the comoving baryon density. This latter quantity scales as $r^{-2-\mu}$ up to the saturation radius, and as r^{-2} in the coasting phase. The Lorentz factor of the photosphere is $\Gamma_{\text{ph}} = (r_{\text{ph}}/r_0)^\mu$ if the photosphere occurs in the acceleration phase, and it is η otherwise. All this put together results in a peak energy dependence

$$\varepsilon_{\text{peak}} \propto \begin{cases} L^{\frac{3\mu-1}{4\mu+2}} \eta^{-\frac{3\mu-1}{4\mu+2}} r_0^{\frac{-5\mu}{4\mu+2}} \epsilon_e^2 \Gamma_r^3 / (1+z) & \text{if } \eta > \eta_T \\ L^{-1/2} \eta^3 \epsilon_e^2 \Gamma_r^3 / (1+z) & \text{if } \eta < \eta_T. \end{cases} \quad (3)$$

We provide exact values for the representative cases discussed here in Section 4.

Thermal peak Besides the synchrotron component we expect also a (modified) thermal component from the photosphere. This component is observed as a thermal peak and it is advected from the launching radius, and cooled according to the generalized dynamics. We present concrete values for the temperature in Section 4, here we only show the general dependence on the parameters:

$$T_{\text{obs}}(r_{\text{ph}}) \propto \begin{cases} L^{\frac{14\mu-5}{12(2\mu+1)}} \eta^{\frac{2-2\mu}{6\mu+3}} r_0^{-\frac{10\mu-1}{6(2\mu+1)}} / (1+z) & \text{if } \eta > \eta_T \\ L^{-5/12} \eta^{8/3} r_0^{1/6} / (1+z) & \text{if } \eta < \eta_T. \end{cases}$$

There were hints of a separate thermal component below the Band peak (Page et al. 2011; Guiriec et al. 2011; Zhang et al. 2011; McGlynn & Fermi Collaboration 2012) in previous bursts, and there are reportedly significant thermal components also in GRB 110721A (Axelsson et al. 2012).

4. EXTREME MODELS

Here we consider the $\varepsilon_{\text{peak}} - L$ pairs for different μ values to show that in the framework of a dissipative photosphere, the high peak energy of GRB110721A can be obtained in a straightforward manner.

From Equation 3, $\eta > \eta_T$ case (photosphere in the acceleration phase), one sees that higher luminosities, and lower Lorentz factors and launching radii, will result in larger peak energies. Increasing L and decreasing r_0 will increase η_T eventually leading to the $\eta < \eta_T$ case (photosphere in the coasting phase). This transition is shown by the break in the evolution of $\varepsilon_{\text{peak}}$ with luminosity (see Figures 1 and 2 and note that in the extreme magnetic case, the peak energy does not depend on the luminosity).

Figures 1 and 2 show that the observed highest peak energy- luminosity pair for GRB 110721A is in the admissible region of the diagrams, and for other reasonable parameters the peak energy is comfortably within the operating range of these models (admissible regions are under the modeled broken power laws, represented by dotted, dashed and dash-dotted lines).

Here we present cases to illustrate the peak energy dependence of the luminosity, and show that within dissipative synchrotron photospheric models we can reproduce the high peak energy. We have taken a redshift $z = 0.382$ (Berger 2011) for the calculations presented here. The luminosity values in the time bins are scattered around $L = 10^{52}$ erg/s (see e.g. Figure 1) thus we take this as a reference value.

4.1. Baryonic photosphere model ($\mu = 1$)

In this model, the magnetic field is subdominant, the dynamics are governed by the baryons in the outflow. The critical Lorentz factor is $\eta_T \approx 740 L_{52}^{1/4} r_{0,7}^{-1/4}$, which puts the photosphere in the coasting phase for moderately high $\eta \lesssim 600$ values. The peak energy will become: $\varepsilon_{\text{peak}} \approx 16 L_{52}^{-1/2} \eta_{2.5}^3 \Gamma_{r,0.1}^3 \epsilon_{B,-1}^{1/2}$ MeV. This is the right order of magnitude for not too extreme parameter values. Lending further support for this model (the baryonic variant) is the temperature of the thermal component, which also turns out the right order of magnitude, $T \approx 70 L_{52}^{-5/12} \eta_{2.6}^{8/3} r_{0,7}^{1/6}$ keV.

4.2. Extreme magnetic model ($\mu = 1/3$)

In this extreme case the break energy does not depend on the luminosity, nor the coasting Lorentz factor. Still, for reasonable values, we can get (see equation 3) a peak value $\epsilon_{\text{peak}} \approx 13 r_{0,7}^{-1/2} \Gamma_{r,0.5}^3 \epsilon_{B,0}^{1/2}$ MeV. The temperature of the blackbody radiation is $T \approx 3 L_{52}^{-1/60} \eta_{2.5}^{4/15} r_{0,7}^{-7/30}$ keV. The dependence on the parameters is weak and this model cannot account for the observed temperature of the black-body component.

4.3. Moderate magnetic model ($\mu = 0.5$)

Here magnetic fields are dominant, but the role of baryons is more marked than in the extreme magnetic case. The peak energy in this intermediate variant of the model is $\epsilon_{\text{peak}} \approx 14 L_{52}^{1/8} \eta_{2.5}^{-1/8} r_{0,7}^{-5/8} \Gamma_{r,0.1}^3 \epsilon_{B,0}^{1/2}$ MeV. Again, this model can incorporate the rather large peak energy for not too exceptional parameters. The temperature of the black-body is lower than in the baryonic photosphere case, $T \approx 24 L_{52}^{1/12} \eta_{2.5}^{1/6} r_{0,7}^{-1/3}$ keV, but might still be consistent with the observations.

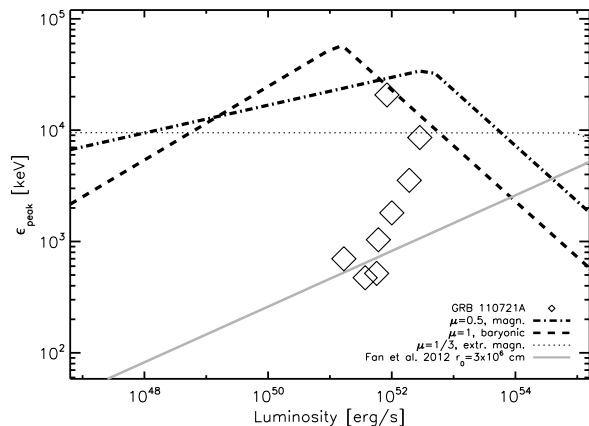


FIG. 1.— GRB 110721A values of spectral peak energy versus peak luminosity for different time bins advancing from top to bottom (diamonds, from Zhang et al. (2012)), compared to expected limiting values from dissipative synchrotron photosphere models (dashed: baryonic $\mu = 1$, dotted: extreme magnetic $\mu = 1/3$, dot-dashed: moderate magnetic $\mu = 0.5$ (this work)). These lines are an upper limit: values of ϵ_{peak} and L below them are allowed. Thus, moderate magnetic and baryonic dissipative photospheres are compatible with the highest peak energy values observed, and even the extreme magnetic case is within a standard deviation. The parameters used are: for $\mu = 1/3$: $r_0 = 10^7$ cm, $\epsilon_B = 1$, $\Gamma_r = 2$, for $\mu = 0.5$: $r_0 = 10^7$ cm, $\epsilon_B = 1$, $\Gamma_r = 1.2$, for $\mu = 1$: $r_0 = 10^8$ cm, $\epsilon_B = 0.1$, $\Gamma_r = 1.2$, and $\eta = 300$ throughout. The solid gray line is a standard (non-dissipative) photosphere curve following Fan et al. (2012), confirming the conclusion of Zhang et al. (2012) that non-dissipative photospheres cannot explain the highest peak energies.

5. DISCUSSION

We have considered the high peak energy values of the prompt spectrum of GRB 110721A, which reach as high as $\epsilon_{\text{peak}} \sim 15$ MeV (Axelsson et al. 2012). A consideration of the usual internal shock prompt emission spectrum model shows that such high values are unlikely in this model. Furthermore, we confirm the conclusion

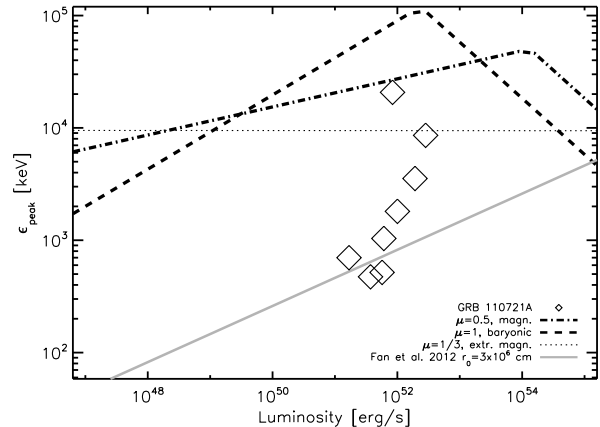


FIG. 2.— Same notation and parameters as Figure 1, except for the coasting Lorentz factor, which is $\eta = 600$ here.

of Zhang et al. (2012) that a (non-dissipative) standard black-body baryonic photosphere model also cannot explain such high peak values and fluxes. However, we show that dissipative photospheric models, with a typical peak energy due to synchrotron radiation, are able to accommodate such high peak energies and flux values, with reasonable parameters, for cases where the dynamics is either baryonically or magnetically dominated. If the temperature of the putatively observed black-body component can be used as a discriminant, this would seem to favor a more baryon dominated dissipative photosphere model, μ closer to 1, although a moderate magnetically dominated photosphere may also be possible.

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